

# Energy bursts from deconfinement in high-mass twin stars

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## ABSTRACT

We estimate the energy reservoir available in the deconfinement phase transition induced collapse of a neutron star to its hybrid star mass twin on the "third family" branch, using a recent equation of state of dense matter. The available energy corresponding to the mass-energy difference between configurations is comparable with energies of the most violent astrophysical burst processes. An observational outcome of such a dynamical transition might be fast radio bursts, specifically a recent example of a FRB with a double-peak structure in its light curve.

*Subject headings:* stars: neutron — radiation mechanisms: non-thermal — gamma-ray bursts: general — pulsars: general

## 1. Introduction

Research on the neutron stars' (NS) equation of state (EoS) is currently a very active area. Numerous observations have changed our understanding of the cold, dense nuclear matter in compact star interiors. Recently, accurate determination of the high mass of about  $2 M_{\odot}$  for PSR J0348+0432 (Antoniadis et al. 2013) and PSR J1614-2230 (Demorest et al. 2010) pulsars has provided a powerful constraint for the stiffness of the EoS. On the other hand, radius measurements are not yet precise enough to rule out some of the many alternative EoS models. Among various estimates, frequency resolved pulse shape analysis for the nearest millisecond pulsar (Bogdanov 2013) supports relatively large radii and offers interesting perspectives for future radius measurements as planned with upcoming missions, cf. NICER (Arzoumanian et al. 2014).

Astrophysical models involving NS can account for the observed powerful gamma ray bursts

(GRB, Klebesadel et al. 1973) emission, where the typical total energy release is of about  $10^{48}$  -  $10^{50}$  erg s<sup>-1</sup> (Cavallo & Rees 1978; Paczynski 1986; Eichler et al. 1989). Other energetic phenomena like fast radio bursts (FRB) - millisecond duration radio bursts from seemingly cosmological distances (Lorimer et al. 2007), for which a model of a NS collapse to a black hole was proposed (Falcke & Rezzolla 2014), as well as natal pulsar kicks (Podsiadlowski et al. 2005; Lai et al. 2001; Kusenko 2005; Berdermann et al. 2005; Stasielak et al. 2007) are associated with comparably high amounts of energy.

This Letter considers the energy release during a dynamical NS collapse induced by a deconfinement phase transition in the core of a compact star (a *corequake*). Unlike previous works which estimated the energy reservoir for typical ( $\sim 1.4 M_{\odot}$ ) mass stars (Drago & Tambini 1999; Berezhiani et al. 2002; Aguilera et al. 2004; Zdunik et al. 2008), we employ a recent EoS model derived in Benić et al. (2015) that allows for the formation of a "third family" of compact stars near the maximum mass. For the first time the corequake scenario is considered in which a *high-mass* hadronic NS collapses into a hybrid compact star disconnected from the former by a sequence of unstable configurations (for a recent classification of hybrid stars, see Al-

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ford et al. 2013). The point of instability can be reached by the hadronic NS in a process of dipole-emission spin-down, or accretion-induced spin-up by matter from a companion.

While a direct collapse of a magnetized NS to a black hole is one viable mechanism for the explanation of FRBs (Falcke & Rezzolla 2014), the NS instability and collapse induced by the deconfinement phase transition of the type discussed here would additionally provide an explanation to a double component reported recently for FRB121002 by Champion (2015) with a light curve peak separation of about 5 ms. In this case, the NS would undergo a corequake transition to a meta-stable twin hybrid NS configuration, which would generate the first peak, before the ultimate collapse to a black hole, generating the second peak, as in Falcke & Rezzolla (2014) model.

## 2. High-mass twin equation of state

The NS mass twin scenario describes the situation in which two stars have the same gravitational mass but different radii due to qualitatively different internal composition: one of them is purely hadronic while the other (the *twin*) is a hybrid star whose core contains quark matter (Gerlach 1968; Kämpfer 1981; Schertler et al. 2000; Glendenning & Kettner 2000; Dexheimer et al. 2015). High mass NS twins (Benić et al. 2015) can potentially identify a critical endpoint in the QCD phase diagram (Alvarez-Castillo & Blaschke 2015; Blaschke et al. 2013). At the same time they provide an attractive solution to actual problems of compact star physics discussed in Blaschke & Alvarez-Castillo (2015): the masquerade phenomenon (Alford et al. 2005), the hyperon puzzle (Baldo et al. 2003), and the reconfinement problem (Lastowiecki et al. 2011; Zdunik & Haensel 2013). An assessment of NS twin identification has been recently carried out (Ayriyan et al. 2014; Alvarez-Castillo et al. 2015; Blaschke et al. 2014).

NS models presented here are based on the DD2 hadronic EoS with excluded volume correction resulting from the quark substructure of nucleons (protons and neutrons) originating from Pauli blocking effects at the level of quark substructure (Röpke et al. 1986). At suprasaturation densities this correction is necessary and has the immediate effect of stiffening the EoS. High NS masses are

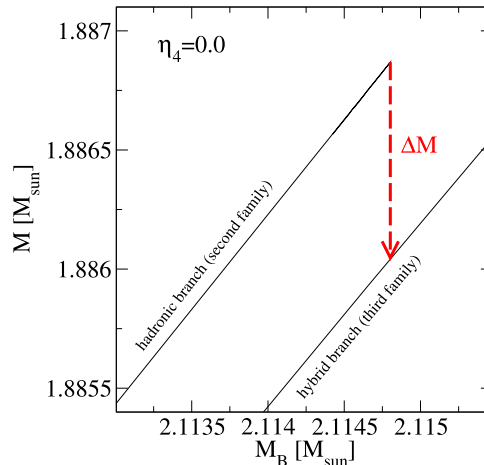


Fig. 1.— Gravitational mass  $M$  vs. baryonic mass  $M_B$  for the hybrid EoS model with vector coupling parameter  $\eta_4 = 0.0$ . Dynamical NS instability induced by a strong first order phase transition: the last stable configuration on the hadronic branch (initial state) is connected with the final hybrid star configuration at the same baryonic mass with a dashed red arrow line. Length of the line represents the mass difference (energy reservoir) occurring in this transition. The results for  $\eta_4 = 5.0, 10.0$  are qualitatively and quantitatively similar.

reached already at moderate densities but large radii ( $\simeq 13 - 15$  km, Blaschke et al. 2013). At higher densities this EoS undergoes a phase transition to quark matter described by a NJL EoS with multiquark interactions first introduced in Benić (2014). The coupling strength parameter in the vector channel of the 8-quark interaction ( $\eta_4$ ) determines a sufficient stiffening of the quark matter EoS at high densities to preserve the maximum observed star mass of  $2 M_\odot$  in this class of models.

## 3. Results and discussion

The EoS of Benić et al. (2015) features the possibility of first order phase transitions substantial enough to destabilize the NS. The appearance of a small, sufficiently dense quark core makes some configurations unstable against radial

oscillations (see e.g. Shapiro & Teukolsky 1986) and is therefore not realized in astrophysical settings. On the mass-radius  $M(R)$  diagram for non-rotating stars these configurations are characterized by  $\partial M/\partial \lambda_c < 0$ , where  $\lambda_c$  is an EoS parameter labelling the configurations (e.g., their central density). Figure 1 traces the subsequent evolution - a dynamical collapse - of an unstable compact star from the point of the maximum mass  $M_{\max,h}$  on the hadronic branch to the corresponding one on the hybrid star branch. For simplicity we assume that the baryon mass  $M_B$  is conserved during the collapse. Figure 2 summarizes the radius

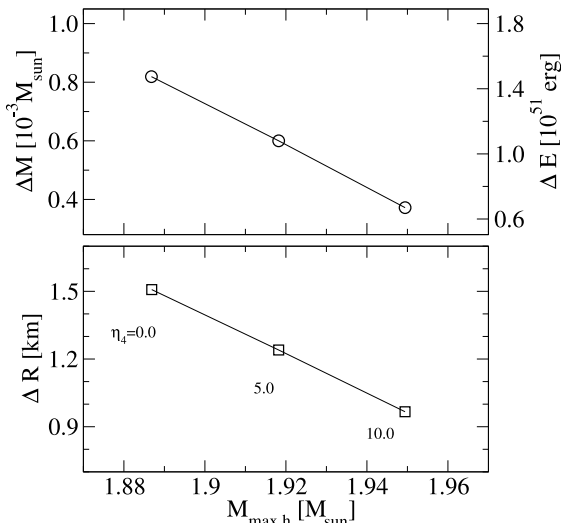


Fig. 2.— Mass difference  $\Delta M$  (upper panel) and radius difference  $\Delta R$  (lower panel) resulting from an instability and subsequent NS collapse induced by a deconfinement phase transition for a set of vector coupling parameters  $\eta_4$  of the high-mass twin EoS models. An associated energy release  $\Delta E$  is indicated on the right side of the upper panel.

change  $\Delta R$  in the transition, which is between 1 km and 1.5 km for the coupling constant range considered. The energy reservoir  $\Delta E$  available in the transition, defined as the mass-energy difference  $\Delta M c^2$  between the initial and final configurations, amounts to roughly  $10^{51}$  erg. We note that in case of the EoS employed in Zdunik et al. (2008) the energy release depends weakly on the rotation rate; rotating configurations and the de-

pendence of the energy reservoir on the rotation rate for EoS of Benić et al. (2015) will be studied in a subsequent article (Bejger et al. 2015).

In conclusion, the energy reservoir available in a high-mass NS instability induced by the deconfinement phase transition is comparable with values measured in burst phenomena associated with most energetic astrophysical processes. It is clear that the deconfinement phase transition in compact stars might play an important role, perhaps as an engine for GRBs or as an additional mechanism supporting the explosion of core collapse supernovae, with an accompanied characteristic neutrino signals. A magnetized NS that is collapsing in a dynamical timescale ( $\simeq 1$  ms) to another, compact configuration may also be attractive in the context of FRBs, specifically in view of recent observations of FRB121002 (Champion 2015) with a double peak light curve structure. Finally, we note that the NS EoS is a key input for scenarios of cosmic ray generation like supernova explosions and NS mergers. Further studies to expose the details of astrophysical observables in the case of NS instabilities induced by dense-matter phase transitions are work in progress (Bejger et al. 2015).

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## REFERENCES

- Aguilera, D. N., Blaschke, D., & Grigorian, H. 2004, *A&A*, 416, 991
- Alford, M., Braby, M., Paris, M., & Reddy, S. 2005, *ApJ*, 629, 969
- Alford, M. G., Han, S., & Prakash, M., 2013, *Phys. Rev. D* 88, 083013
- Alvarez-Castillo, D. E., Ayriyan, A., Blaschke, D., & Grigorian, H. 2015, arXiv:1506.07755

- Alvarez-Castillo, D. E., & Blaschke, D. 2015, PoS CPOD 2014 (2014) 045
- Antoniadis, J., Freire, P. C. C., Wex, N., et al. 2013, *Science*, 340, 448
- Arzoumanian, Z., Gendreau, K. C., Baker, C. L., et al. 2014, *Proc. SPIE*, 9144, 914420
- Ayriyan, A., Alvarez-Castillo, D. E., Blaschke, D., Grigorian, H., & Sokolowski, M. 2014, arXiv:1412.8226
- Baldo, M., Burgio, G. F., & Schulze, H. -J. 2003, *Superdense QCD Matter and Compact Stars*, D. Blaschke and D. Sedrakian (Eds.), Springer, Heidelberg, 2006, p.113
- Bejger, M., et al., 2015, in preparation
- Benić, S. 2014, *Eur. Phys. J. A*, 50, 111
- Benić, S., Blaschke, D., Alvarez-Castillo, D. E., Fischer, T., & Typel, S. 2015, *A&A*, 577, A40
- Berdermann, J., Blaschke, D., Grigorian, H., & Voskresensky, D. N. 2006, *Prog. Part. Nucl. Phys.* 57, 334
- Berezhiani, Z., Bombaci, I., Drago, A., Frontera, F., & Lavagno, A. 2002, *Nucl. Phys. B Proc. Suppl.*, 113, 268
- Blaschke, D., Alvarez-Castillo, D. E., & Benic, S. 2013, PoS CPOD 2013 (2013), 063
- Blaschke, D. B., Grigorian, H. A., Alvarez-Castillo, D. E., & Ayriyan, A. S. 2014, *J. Phys. Conf. Ser.*, 496, 012002
- Blaschke, D., & Alvarez-Castillo, D. E. 2015, arXiv:1503.03834
- Bogdanov, S. 2013, *ApJ*, 762, 96
- Cavallo, G., & Rees, M. 1978, *MNRAS*, 183, 359
- Champion, D., 2015, talk at seventh Bonn Workshop on "Formation and Evolution of Neutron Stars", May 18, 2015
- Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E., & Hessels, J. W. T. 2010, *Nature*, 467, 1081
- Dexheimer, V., Negreiros, R., & Schramm, S. 2015, *Phys. Rev. C*, 91, 055808
- Drago, A., & Tambini, U. 1999, *J. Phys. G*, 25, 971
- Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, *Nature*, 340, 126
- Falcke, H., & Rezzolla, L. 2014, *A&A*, 562, A137
- Gerlach, U. H. 1968, *Phys. Rev.*, 172, 1325
- Glendenning, N. K., & Kettner, C. 2000, *A&A*, 353, L9
- Kämpfer, B. 1981, *J. Phys. A*, 14, L47
- Klebesadel, R. W., Strong, I. B., & Olson, R. A. 1973, *BAAS*, 5, 322
- Kusenko A. 2005, *Int. J. Mod. Phys. A*, 20, 1148  
2001, *ApJ*, 549, 1111
- Lai, D., Chernoff, D. F., & Cordes, J. M. 2001, *ApJ*, 549, 1111
- Lastowiecki, R., Blaschke, D., Grigorian, H., & Typel, S., 2012, *Acta Phys. Polon. Supp.* 5, 535
- Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, *Science*, 318, 777
- Paczynski, B., 1986, *ApJ*, 308, L43
- Podsiadlowski, P., Pfahl, E., & Rappaport, S. 2005, *Binary Radio Pulsars*, 328, 327
- Röpke, G., Blaschke, D., & Schulz, H., 1986, *Phys. Rev. D* 34, 3499
- Schertler, K., Greiner, C., Schaffner-Bielich, J., & Thoma, M. H. 2000, *Nucl. Phys. A*, 677, 463
- Shapiro, S. L., Teukolsky, S. A., *Black Holes, White Dwarfs and Neutron Stars: The Physics of Compact Objects*, 1986, Wiley, New York
- Stasielak, J., Biermann, P. L., & Kusenko, A. 2007, *ApJ*, 654, 290
- Zdunik, J. L., Bejger, M., Haensel, P., & Gourgoulhon, E., 2008, *A&A*, 479, 515
- Zdunik, J. L., & Haensel, P. 2013, *A&A*, 551, A61

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